Synopsis of the thesis entitled:

Evolution of Cambay Basin, western India during the Eocene from the study of gastropods and shell beds

by

Sayoni Banerjee

Registration no. R-18RS15210147

Supervised by

Prof. Kalyan Halder

Department of Geology

Presidency University

Introduction

Fossil records of gastropods are interesting windows into the geologic past because of their external hard shells with good preservation potential, remarkable adaptability within deep marine to terrestrial habitats, intricate interplay with changing environment, diverse developmental strategies, ability to disperse over long distances in oceans, etc. Many important groups of gastropods, abundant and diverse in today's ecosystems, first appeared and proliferated during the early Cenozoic. The early Cenozoic history of gastropods including their diversity, ecology and distribution is largely based on the fossil records obtained from basins situated on the western side of the former Tethys Sea, which is considered to be the biodiversity hotspot of the time. Meanwhile, contemporary gastropods of India, at the eastern side of the Tethys, remained relatively less explored.

This research is focused on the Cambay Basin, situated in the western margin of India. It belongs to the Western Indian Province (WIP), a palaeobiogeographic province of the Paleogene period (Harzhauser *et al*. 2009, Das & Halder 2018). Comprehensive monographs of gastropods from the basins of Pakistan, included within the WIP, are available. Contemporaneous rocks with diverse gastropod assemblages are preserved in the Indian basins of WIP such as Kutch, Rajasthan and Subathu. However published reports from these basins are sporadic compared to the basins of Pakistan.

All these basins were flooded by marine transgression during the early Eocene. Terrestrial and marine sediments bearing fossils of terrestrial and marine animals were deposited alternatively in response to fluctuating sea levels. The early Eocene (Ypresian) rocks of Cambay Basin, known as 'Cambay Shale', is made up of alternating layers of lignite, variegated shale and limestone. The Cambay Shale became accessible to researchers due to the lignite explorations in four mines - Mangrol, Vastan, Tadkeswar and Valia. Molluscs,

including gastropods and bivalves, are found within variegated shales, bioclastic limestones, and also as shell concentrations. The depositional history of these mollusc-bearing beds has not been studied in detail before.

Provincialism in specific and cosmopolitanism in generic distribution is observed in many Palaeogene mollusc assemblages from the basins of WIP, including Cambay (Iqbal 1969a, b, 1972; Halder & Sinha 2014; Halder & Das 2019; Das 2019; Harzhauser *et al*. 2009; Kulkarni *et al*. 2010). Their geographic distributions are guided by several factors such as the surface ocean currents, early developmental mode, temporal range, climatic shifts, depositional environment, etc.

In this backdrop, the main objectives of this study are -

1) To document the Ypresian gastropods of the Cambay Basin and make a detailed taxonomic report on them.

2) To reconstruct the palaeoecology and palaeoenvironment of the Cambay Basin during the Ypresian from the mollusc compositions and their stratigraphic distributions within the Cambay Shale.

3) To understand the palaeobiogeographic evolution of the gastropods of the Cambay Basin, in the backdrop of WIP during Palaeogene.

Previous studies regarding the objectives -

1) No gastropods from the Ypresian of Cambay Basin had been reported before.

2) The palaeoenvironment of this basin was studied from sedimentological, micropalaeontological and palynological evidences, collected mainly from the Cambay Shale

in Vastan north pit, and also in the Tadkeswar mine (Sahni *et al*. 2006; Prasad *et al*. 2013; Samanta *et al*. 2016). No study was conducted based on molluscs present in this formation.

3) The Cambay Basin gastropod fauna is new and thus its palaeobiogeographic evolution is unknown. The specific endemism in contrast to wide generic distribution, the relation of the distribution pattern with early developmental mode, and dispersal of the genera by prevailing surface currents were highlighted in previous studies involving the contemporaneous gastropod faunas from other basins of WIP, such as Kutch, western India and the Pakistan basins (Iqbal 1969a, b, 1972; Halder & Sinha 2014; Halder & Das 2019).

Geological setting. The catastrophic volcanism of the Deccan Traps in the Upper Cretaceous changed the landscape of western India. The Paleocene Vagadkhol Formation, consisting of terrigenous variegated claystones, conglomerates and sandstones, is exposed locally above the Deccan Traps (Chandra & Chowdhary 1969; Sudhakar & Basu 1973). A ~ 40 m thick sedimentary formation, known as 'Cambay Shale', overlies the Vagadkhol Formation and Deccan Traps. This unit contains marine fossils and limestones indicating marine incursion in response to widespread early Eocene transgression. It is exposed and accessible in four open-pit lignite mines including Mangrol, Vastan, Tadkeswar and Valia in Gujarat, western India (Fig. 1).

The age of Cambay Shale is known from a series of studies involving age-diagnostic foraminifers and dinoflagellates (Garg *et al*. 2008; Punekar & Saraswati 2010) and from isotope ratios (Clementz *et al*. 2011; Samanta *et al*. 2013; Khozyem *et al*. 2021). All the significant early Eocene hyperthermal events, e.g., PETM, ETM2/H1, H2, I1 and I2 had been recorded from this formation (Clementz *et al*. 2011; Samanta *et al*. 2013). The Cambay Shale is overlain by the late Eocene Amravati Formation, comprising foraminiferal limestones, marls and sandstones (Nagori *et al*. 2013).

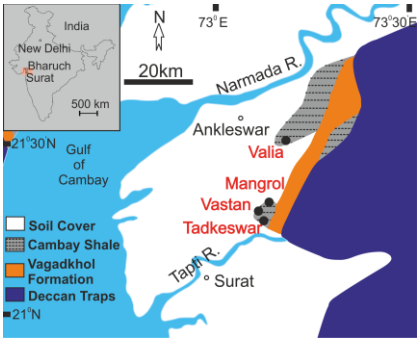


Figure 1. Geological map of a part of the Cambay Basin (modified after Sahni *et al*. 2006).

<u>Litho- and bio-stratigraphy of Cambay Shale</u>. Several vertical sections of Cambay Shale were studied, and rocks and fossils were collected in five field visits to the lignite mines.

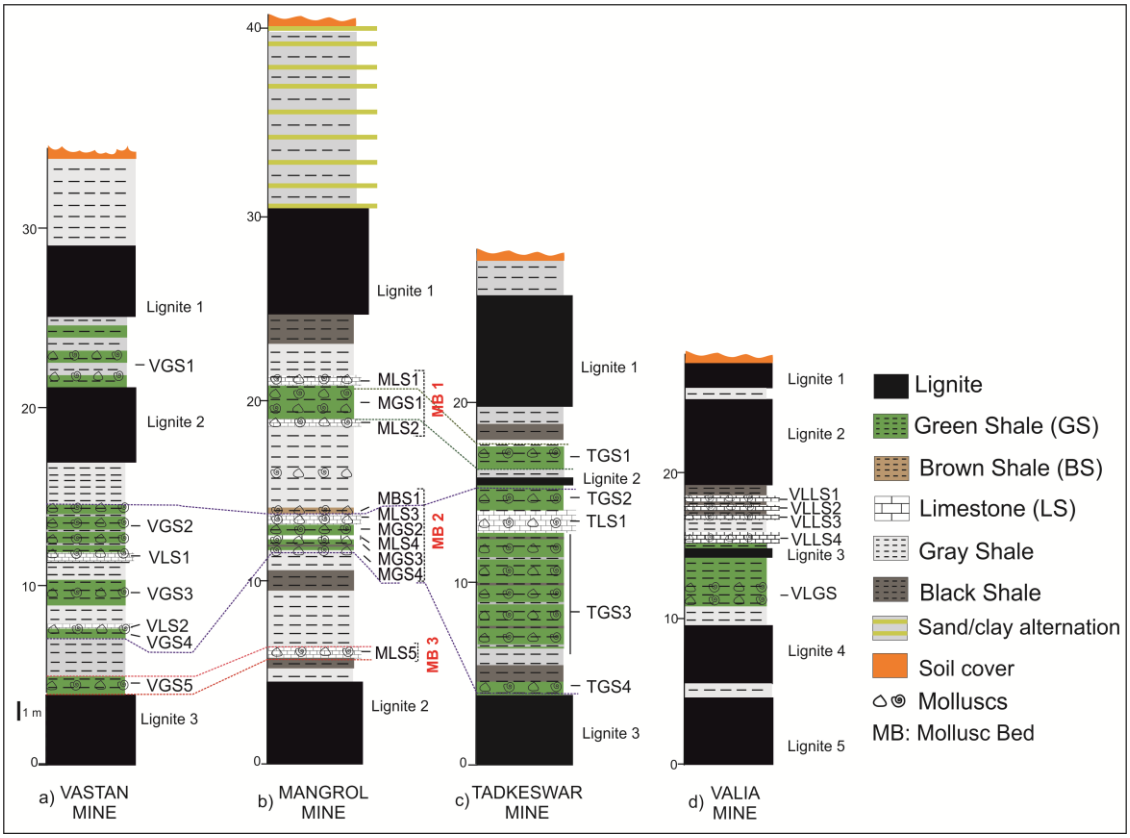


Figure 2. Lithostratigraphic sections of the Cambay Shale in a) Vastan, b) Mangrol, c) Tadkeswar and d) Valia mines. The mollusc-bearing levels are indicated in the figure.

Two/three lignite seams alternating with variegated shales and limestones, with subordinate number of fine-grained sandstones characterize the Cambay Shale in most of the studied sections (Fig. 2a-d). Chiefly the glauconitic green shale layers within the variegated shales contain intact marine fossils. Only in Valia, several lignite seams are intercalated with variegated shales having scarce marine fossils. In the Mangrol mine, which yielded maximum fossils, the molluscs are dispersed in three different beds, referred to as 'Mollusc Beds' (MB) here. The lower-most bed, MB3, a bioclastic limestone, is also the thinnest. MB1 and MB2, defining the main marine interval, are intercalations between mainly fragmented shell-bearing limestones (MLSs), and green and brown shales (MGS/MBSs) with numerous intact mollusc shells. Layered carbonate concretions are also intercalated with these units. The upper part of Cambay Shale, above Lignite 1, is an alternation between fine sandstone and grey to white claystone. This part lacks mollusc fossils. The main mollusc-bearing levels of the Vastan and Tadkeswar mines occur in between Lignite 2 and 3 of these mines. The lithology and mollusc composition of these mines are similar to that of the Mangrol mine.

(1) SYSTEMATIC PALAEONTOLOGY:

1.1. MATERIALS & METHODS. The gastropod species are identified based on morphological study. Many published literatures were consulted including reports from the Kutch, Rajasthan and Subathu basins of India, Sulaiman, Kohat-Potwar and Kirthar basins of Pakistan, and basins from Middle East countries, European and African countries, North and South American countries, Australia and New Zealand. The online catalogue of Muséum national d'Histoire naturelle, Paris, France (https://science.mnhn.fr/institution/mnhn/search) was consulted frequently.

1.2. RESULTS & DISCUSSION. A total of 40 species are identified up to specific level. 3 species are identified up to generic level. Most of them have well-preserved aragonitic shells, and a few of them are represented by internal moulds. 34 among them belong to the subclass Caenogastropoda and the remainder 9 to Heterobranchia. 15 of these are minute (Height < 3 mm) in adult size. 33 out of these 43 species are new species, restricted to this basin only. 3 new genera and 2 new subgenera are introduced in this work.

Subclass: Caenogastropoda

1.2.1. Superfamily Campaniloidea. This superfamily is represented by two families, Ampullinidae and Gyrodidae, in the Cambay Shale. The identified species are - a) *Amaurellina cambayensis* sp. nov., b) *Ampullina brevipira* (Leymerie, 1846), c) *Ampullina vastanensis* sp. nov. and d) *Gyrodes eocenicus* sp. nov. Another species identified as *Crommium* could not be given a specific identity because it is represented by only one poorly preserved specimen. Among these only *Ampullina brevispira* was known from the Paleocene of Pakistan and the middle Eocene of southern France. Others are new species. The report of *Gyrodes eocenicus* from Cambay Shale is significant because it is the first confirmed report of this genus from the Cenozoic. *Gyrodes* was a Cretaceous genus with enormous diversity and distribution. It is represented by only a few doubtful species from the Cenozoic. The unique diagnostic characters of only the new species are briefly mentioned below.

a) *Amaurellina cambayensis* sp. nov. – Minute size; weakly developed shelf; angular shoulder; thin umbilical lamella.

b) *Ampullina vastanensis* sp. nov. – Elevated-rounded spire whorls, adaxially inclined sub-sutural ramp and rounded shoulder; semi-circular aperture; small, slit-like umbilicus; prominent umbilical sheath, bounded by a well-defined rim; prominently reflected inner lip.

c) *Gyrodes eocenicus* sp. nov. – Sub-rhombic shell; flat spire whorls with moderately wide, adaxially inclined ramp and weakly angular shoulder; biangulated last whorl; deep and large umbilicus.

1.2.2. Superfamily Cerithioidea. 13 species belonging to 5 families of this superfamily are reported here. Two of them, *Faunus lamarckii* (Deshayes, 1862) and *Serratocerithium eocenicum* (Cox, 1931), were known from outside of this basin. All other cerithioids are restricted to this basin. *Faunus lamarckii* and *Melanoides khanae* sp. nov. are very abundant in Mangrol and Vastan, respectively.

Two new genera, *Pachycerithium* and *Indobatillaria* are introduced here. *Pachycerithium richardi* gen. et sp. nov., a pachychilid, could not be placed in any known genera. That is why the genus *Pachycerithium* is introduced for this species. On the other hand, *Batillaria coronata* Cox, 1930, previously known only from contemporaneous rocks of Pakistan, was found to possess intermediate characters between *Batillaria* and *Vicinocerithium*. The characters, such as the prominently channelled posterior end of spire whorls, an increasing number of secondary spiral ribs, varices in spire whorls, a varix opposite to the adult aperture, tuberculate spiral ribs placed near suture, are distinct enough to erect a new genus, *Indobatillaria*, within the Batillaridae family. The diagnostic characteristics of the new cerithioid species from the Cambay Basin are as follows –

a) *Pthychocerithium shamukum* sp. nov. - Large size; gently convex spire whorls; absence of varices.

b) *Bittium asimae* sp. nov. - Minute size; protoconch conical-multispiral; convex spire whorls with three equally strong spiral ribs, axial ribs and tubercles at their intersections; base flat and constricted with fine spiral and axial lines; aperture ovate with an anterior siphonal canal.

c) *Bittium kamalae* sp.nov. - Minute size; protoconch conical-multispiral with spiral ornament; strongly convex spire whorls with strong spiral, axial ribs and tubercles at their intersections; base with only spiral keels; ventrolateral varix present.

d) *Bittium purnimae* sp.nov. - Minute size; moderately convex spire whorls with 3 equally strong spiral and 22 axial ribs, numerous weaker spiral and axial lines; varices present.

e) *Indobatillaria ismatae* gen. et sp. nov. - Large size; weakly convex spire whorls; suture canaliculate; later whorls with seven flat-crested strong spiral ribs, sharp rib in posterior channel; strong axials transverse over spiral ribs, obscure later; spirally elongated tubercles at their intersections, sometimes spinose; base with spiral ribs only.

f) *Pseudobellardia sitae* sp. nov. - Flat spire whorls; weakly channelled suture with a wide sub-sutural groove, whorls stepped at anterior margin of groove; spiral ribs present all over whorls, stronger in grooves; axials in later whorls; base flat and short with spiral ribs only.

g) *Pachycerithium richardi* gen. et sp. nov. - Slender; spiral ribs only in early whorls; axial ribs stronger, consistent in all whorls; base with only spirals; long and deflected anterior siphonal canal.

h) *Serratocerithium indicum* sp. nov. - Secondary spiral ribs alternating with primary ribs, becoming as strong as the primaries in last whorl; strong, spirally elongated tubercles; outer lip sinus deep.

i) *Potamides mosaliensis* sp. nov. - Deep sutures with steep sub-sutural ramp; spiral ribs with spirally elongated tubercles, fourth spiral adjacent to anterior suture fine, smooth and sharp; anterior siphonal canal narrow and short.

j) *Potamides shahensis* sp. nov. - Slightly convex spire whorls; all spiral ribs beaded prominently; flat base.

k) *Melanoides khanae* sp. nov. - Small size; reticulate ornament in spire whorls; inner lip calloused with a ridge.

1.2.3. Superfamily Naticoidea: *Natica naroliensis* sp. nov. is the first confirmed report of *Natica* from the Eocene of WIP. Many species were previously identified as *Natica* by d'Archiac & Haime (1854) but reassigned to other naticid/ampullinid genera by later authors. The Cambay species is distinct from most known species in the position of its funicle. Here, the moderately strong funicle is positioned at the adapical side of the umbilicus with a strong sulcus in its middle, contrary to the median funicle with sulcus at both sides in most known species.

1.2.4. Superfamily Rissoidea: *Benthonella prosoclinata* sp. nov., a rissoid, is one of the most dominant gastropods of the Cambay Shale. Another rissoid species is placed in the genus *Alvania*, but its specific identity could not be confirmed. these two species are minute, within 2.1 mm in height. *B. prosoclinata* sp. nov. is only the sixth fossil species of this genus. The prominently prosocline growth lines and strong varices in spire whorls differentiate *B. prosoclinata* from all known species of this genus.

1.2.5. Superfamily Truncatelloidea: A minute, almost planispiral gastropod is identified as a new species of *Teinostoma*. *Teinostoma maryae* sp. nov. is distinguishable from all contemporary species in having minute size, slightly inflated spire whorls, thickened outer lip and absence of fine spiral striations.

1.2.6. Superfamily Stromboidea: While stromboid gastropods were very abundant in the Paleocene-Eocene of Pakistan, *Rimella rokeyae* sp. nov. is the only representative of this

superfamily in the Cambay Basin. It is distinctive in having almost straight axial ribs becoming stronger, concave, and more widely spaced in later whorls, an extended posterior siphonal canal terminating after crossing the apex, and a finely plicated columellar lip.

1.2.7. Superfamily Unassigned: Another new species from the Cambay Shale belonging to the genus *Strepsidura* is reported here. This genus is not yet assigned to any superfamily. In the old reports, it was included either in Buccinoidea or Muricoidea. The reticulate sculpture of the Cambay species, *S. reticulata* sp. nov. is characteristic and only observed in a few contemporary Pakistan species. It is also distinctive in having a small and wide shell with coarse ornaments and prominent siphonal fasciole.

1.2.8. Superfamily Volutoidea: The Paleogene volutids are very diverse in WIP, even more diverse than in the western Tethys biodiversity hotspot. This report adds two more species to this list. *Involuta*? *ishwari* sp. nov. and *Prestrombus*? sp. are the largest gastropods present in the Cambay Shale. *Involuta*? *ishwari* sp. nov. has a wider aperture, and a wider and more horizontal shelf compared to the other *Involuta*, described so far. *Lyria* (*Lyrispina*) aff. *cossmanni* Vredenburg, 1923 comb. nov., first reported from the contemporaneous sequence of Pakistan, is one of the most abundant gastropods in the Cambay Shale. Here, a new subgenus *Lyrispina* is introduced within the genus *Lyria* to emphasize the presence of some unique characteristics like deeply channelled sutures with steeply rising narrow ramp, apically extended spinose axial costae on shoulder, a long anterior siphonal canal, and absence of siphonal fasciole, only observed in *L. cossmanni*

1.2.9. Superfamily Buccinoidea: Three new species, belonging to this superfamily are identified here. Among these, *Eopreangeria mangrolensis* gen. et sp. nov. is the most abundant species found in MB1 and MB2 of Cambay Shale from Mangrol mine. The new genus *Eopreangeria*, while share many characters with other buccinoid genera possesses a

unique combination of characters such as a labral tooth at the anterior third of a whorl, axial ribs only in early whorls and strong spiral ribs in later whorls. It is the oldest buccinoid with a labral tooth. The diagnostic characteristics of these species are as follows-

a) *Eopreangeria mangrolensis* sp. nov. – Labral tooth at the anterior third of outer lip; axial ribs only in early spire whorls; a broad and deep siphonal notch.

b) *Siphonalia kalpanae* sp. nov. – Strongly excavated base; numerous, very thin axial ribs; quite deflected anterior siphonal canal.

c) *Siphonalia pritilatae* sp. nov. – Prominently spinose axial ribs; biangulate last whorl.

1.2.10. Superfamily Olivoidea. *Amalda bibhae* sp. nov. is the only olivoid species from the Cambay Shale. It is identified as a new species based on a unique combination of characteristics including its small size, slight concavity at the posterior end of spire whorls, three unequal divisions of the anterior band and denticulate aperture.

1.2.11. Superfamily Conoidea. Conoideans were abundant during the Paleocene-Eocene in WIP. Here, three species are reported among which one is restricted to this basin. *Pleurofusia amphibola* (Cossmann & Pissarro 1909) and *Pyrenoturris soriensis* Eames, 1952 were first found in the Ypresian of Kirthar and Sulaiman basins, respectively. *Apiotoma (Carinotoma) rammohani* subgen. et sp. nov. is restricted to Cambay. The subgenus *Carinotoma* is introduced in this work because of the distinct morphological characters found only within the *Apiotoma* spp, described from Eocene of Pakistan and Cambay. While all other *Apiotoma* spp. are characterized by weak to moderate spiral ribs on whorls and occasionally a weak sutural keel, the WIP spp. look distinct in bearing a prominent, well-projected peripheral keel, and stronger spiral ribs and sutural keels.

Subclass: Heterobranchia

1.2.12. Superfamily Ringiculoidea: Among the heterobranchs, *Ringicula* is one of the most documented genera. *Ringicula maxi* sp. nov. is found abundantly in different horizons within MB2 of Cambay Shale in the Mangrol mine. The most striking feature of this species is the presence of prominent callous knobs in the parietal lip, which is not formed as a continuation of any fold. Such knobs are not observed within this genus, so far. Other distinguishing characteristics are minute size, variable relative widths of spiral bands and their interspaces, change in thickness and spacing of spiral bands from spire to last whorl and denticulate outer lip.

1.2.13. Superfamily Cylichnoidea: Two species from Cambay Shale belong to this superfamily. One of them, *Cylichna minuta* sp. nov. is first reported in this work and another one, *Cylichna (Acrostemma) punjabensis* Eames, 1952, was first found in Ypresian of Sulaiman Basin, Pakistan. Both of them are minute, within 3 mm in height. *Cylichna minuta* sp. nov. is the smallest species of *Cylichna*, described from this time. It possesses wider and more distantly spaced spiral ribs at the anterior end of the shell compared to its contemporary counterparts. It is very abundant in the Cambay Shale sections of the Mangrol, Vastan and Tadkeswar mines.

1.2.14. Superfamily Philinoidea: *Roxania suratensis* sp. nov. is also unique to this basin. It is distinguishable from the known species of *Roxania* in having a minute yet inflated shell, deeper grooves, and spiral ornaments only in the posterior and anterior ends of the whorls.

1.2.15. Superfamily Pyramidelloidea: Five new pyramidellid species are identified here. Four of these have prominent heterostrophic protoconchs preserved. These species are diagnosed by the following characters –

a) *Odostomia concavata* sp. nov. - Moderately high spire of flat to gently concave spire whorls, concavity increases abapically; sutures grooved with sub-sutural margins; a faint spiral band near anterior suture; strongly angular periphery.

b) *Megastomia canaliculata* sp. nov. - Significant contraction of whorls below a strongly angular periphery; canaliculate periphery.

c) *Megastomia carinata* sp. nov. - Strong keels at both ends of whorls; shallow suture with narrow sub-sutural ramp.

d) *Costosyrnola taptiensis* sp. nov. - Straight axial ribs separated by wider interspaces; ribs abruptly terminating at periphery.

e) *Cingulina franki* sp. nov. - Four strong spiral keels making spire whorls appear strongly concave, weak spiral and axial lines between keels; last whorl with similar shape and sculpture; periphery rounded; base almost flat.

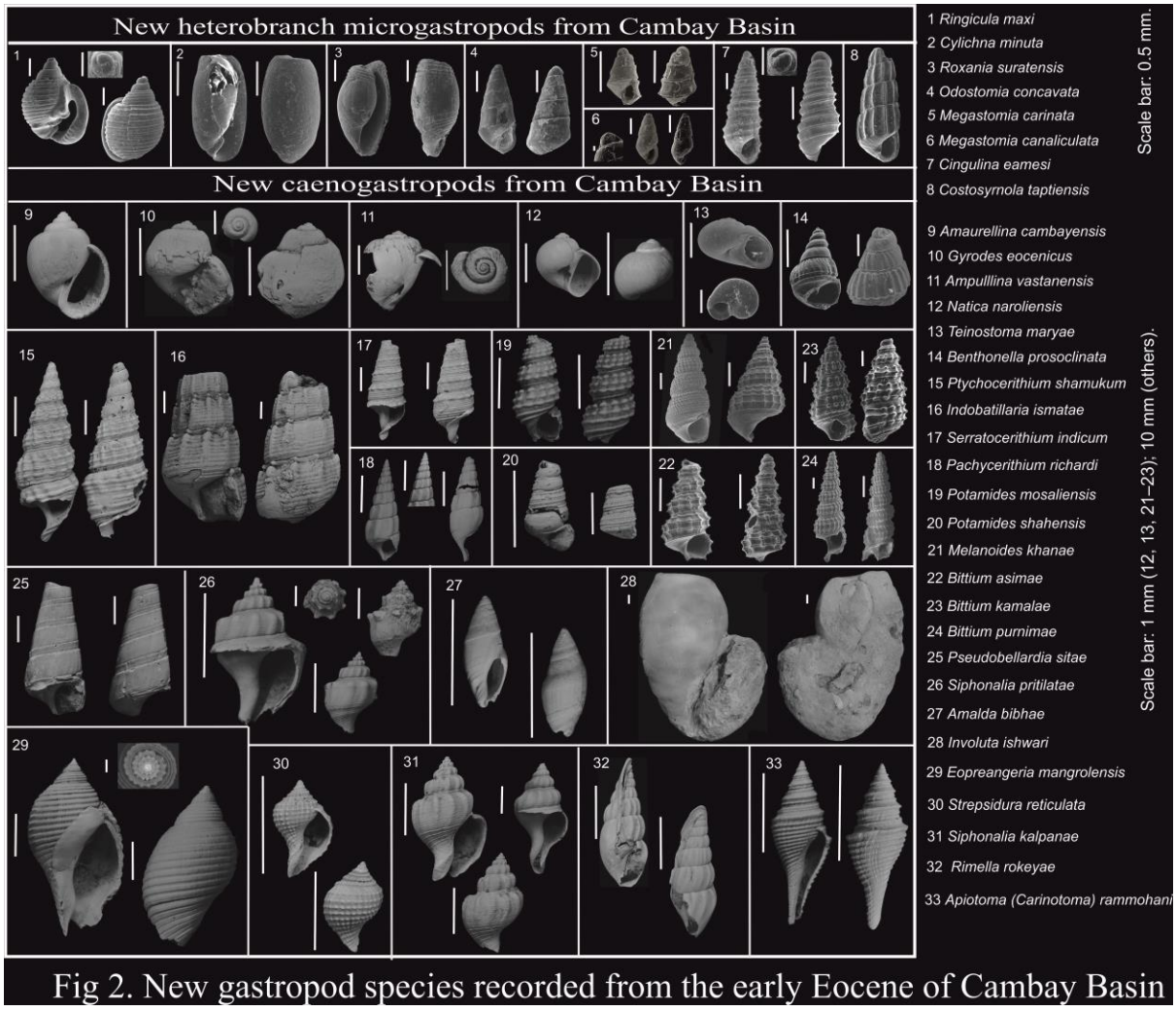


Fig 2. New gastropod species recorded from the early Eocene of Cambay Basin

Figure 3. Photographs of the new gastropod species identified from the Ypresian Cambay Shale, of Cambay Basin, western India.

(2) PALAEOENVIRONMENT AND PALAEOECOLOGY:

The molluscan perspective of the palaeoenvironment and palaeoecology of the Cambay shale is discussed here. The diversity, abundance and stratigraphic distribution data of the bivalves from the Cambay Basin is incorporated in this study along with gastropods to get a comprehensive picture.

2.1. MATERIALS & METHODS. Several quantitative analyses were performed with the abundance data of the bivalves and gastropods present in the Cambay Shale in Mangrol

mine. This study has employed rarefaction analysis to find out sampling bias, rank-abundance models (RAD: Preemption-Zipf-Zipf Mandelbrot-Log Normal-Null in order of increasing evenness and decreasing dominance) to understand the community ecology, diversity indices (DIs: Simpson and Shannon-Wiener for diversity, Berger-Parker for dominance) to quantify and compare the biodiversity of different beds, cluster analysis (CA; based on Bray-Curtis similarity index using UPGMA algorithm) to identify the taxonomic similarities and dissimilarities between the mollusc beds, and Detrended Correspondence Analysis (DCA) to investigate and visualize the trend of change in ecological conditions through stratigraphic levels. The rank-abundance models were generated using the 'vegan' package in R, and all other analyses were performed in PAST 3.20 software (Hammer *et al*. 2001; Oksanen *et al*. 2017). Further, this investigation takes into consideration the environmental and life habit preferences of the living and fossil representatives of all genera as evidenced in published literature.

2.2. RESULTS & DISCUSSION. The palaeoenvironmental condition of these beds is discussed briefly according to the results of the above analyses. The rarefaction curves for the mollusc beds show good to moderate agreements between the sample and species numbers (Fig. 4a-h).

At the base of the sequence there is Lignite 2. It indicates the presence of a swamp. The dominance of brackish-water gastropods like *Faunus lamarckii*, in the lowermost mollusc bed (MLS5/MB3) marks the first phase of marine transgression in this coastal basin. The relatively moderate diversity indices (Fig. 5) reflect the early stage of marine influence. The unique faunal composition of this layer (DCA, Fig. 6a; CA, Fig. 7) and the diversity-abundance pattern (RAD: Zipf, Fig. 8h) suggest an opportunist-dominated community with

specialized ecological requirements flourishing in a restricted coast, close to land (Lit. rev., Fig. 9; see dominance of brackish/freshwater-affiliated and herbivore gastropods).

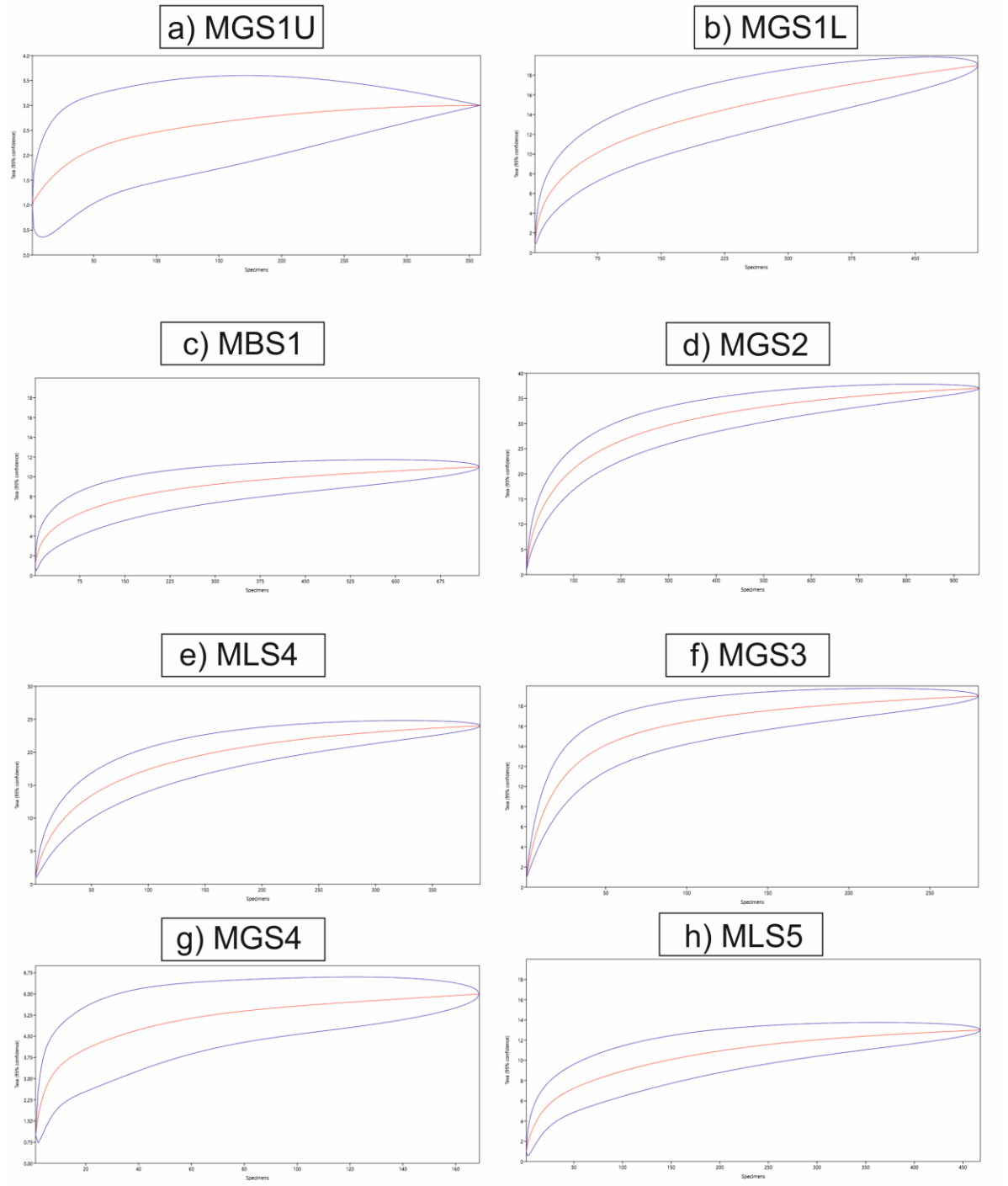


Figure 4. Rarefaction curves for the eight stratigraphic levels of Cambay Shale in Mangrol mine.

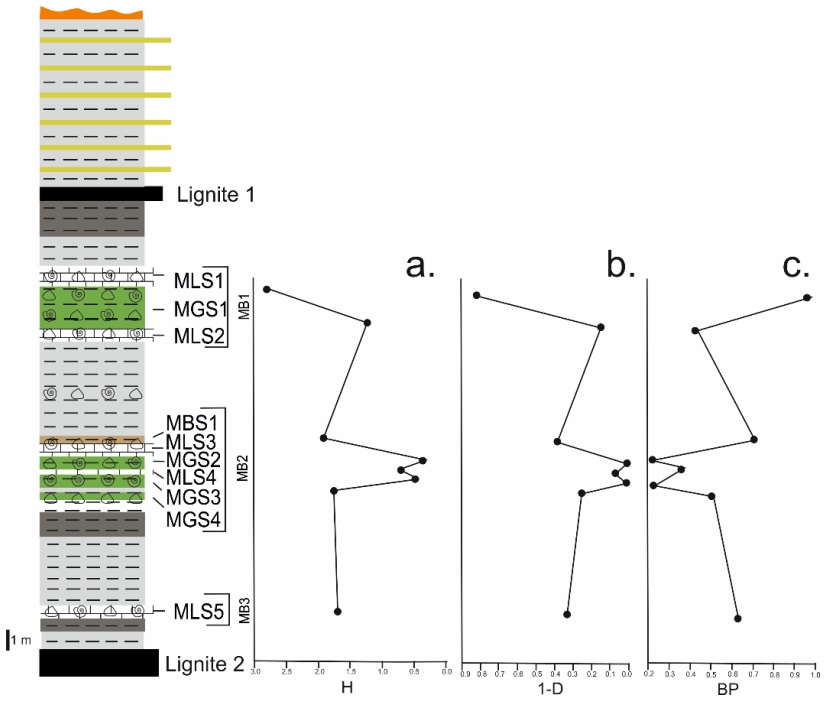


Figure 5. Change in the diversity indices, a) Shannon-Wiener index, b) Simpson's index of diversity, and c) Berger-Parker index, along the mollusc-bearing levels of Cambay Shale in Mangrol mine.

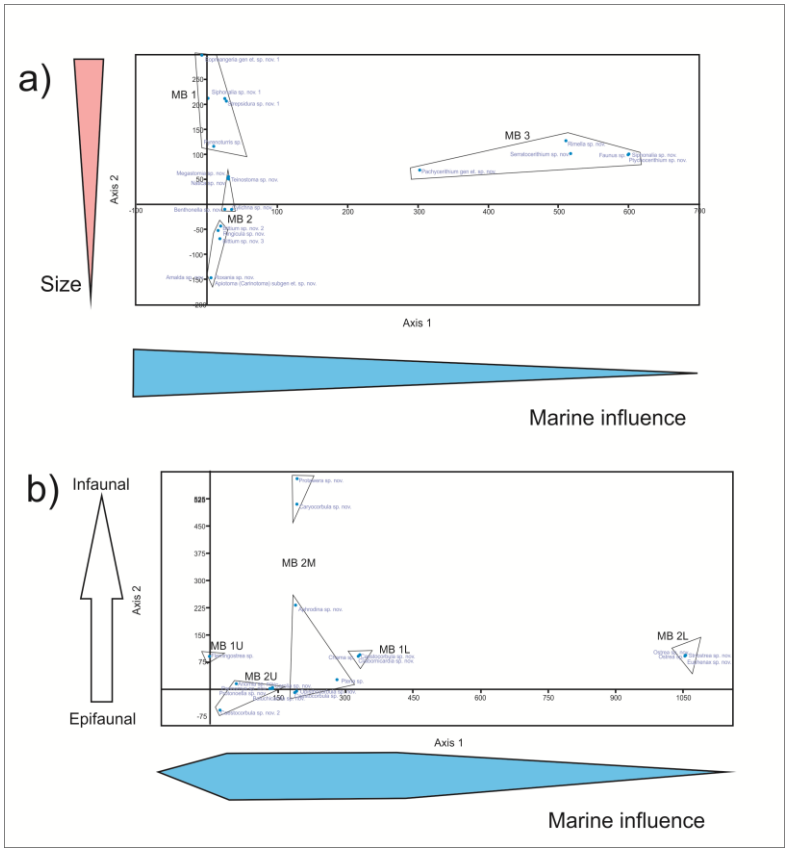


Figure 6. Plots obtained from DCA for a) gastropods and b) bivalves present in the mollusc-bearing levels of Cambay Shale in Mangrol mine.

As the sequence progresses upwards, MB2 shows increasing marine influence (DCA, Fig. 6a, b) and more diverse faunal assemblages,

especially in its middle part (DIs, Fig. 5; Lit. rev., Fig. 9). While the lower part of MB2, MGS4, is characterized by predominance of epifaunal suspension feeder bivalves (dominantly *Ostrea jibananandai* Halder & Mitra, 2021) and a high abundance-low diversity pattern (RAD: Pre-emption, Fig. 8g), the middle part of it is characterized by both infaunal and epifaunal bivalves with the dominance of carditids and corbulids, many epifaunal herbivore and carnivore gastropods, comparatively high diversity-low dominance assemblages (RAD: Null (MGS3), Log-Normal (MLS4), Zipf-Mandelbrot (MGS2), Fig. 8.d-f; DIs, Fig. 5). Maximum faunal sharing occurs between these levels (CA, Fig. 7).

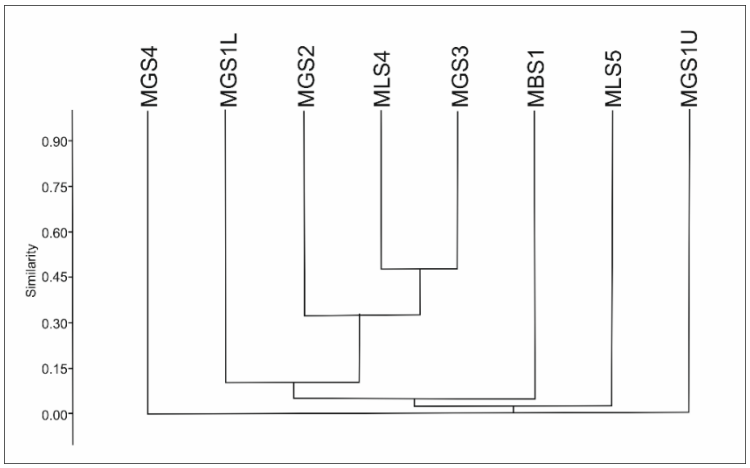


Figure 7. Correlation of the different mollusc-bearing levels in the Mangrol mine, shown in the Cluster Analysis dendrogram.

This part is significant regarding the gastropod fauna because the microgastropod (<3 mm) community is restricted to these layers. Foraminifers and scaphopods are also found. The upper part of MB2 is characterized by a thick bioclastic limestone (MLS3) with only fragmented shells and a thin brown shale (MBS1) having a similar mollusc composition and diversity-abundance pattern (RAD: Mandelbrot, Fig. 8c). However, it has a relatively lower diversity and higher dominance compared with the layers immediately below it (DIs, Fig. 5).

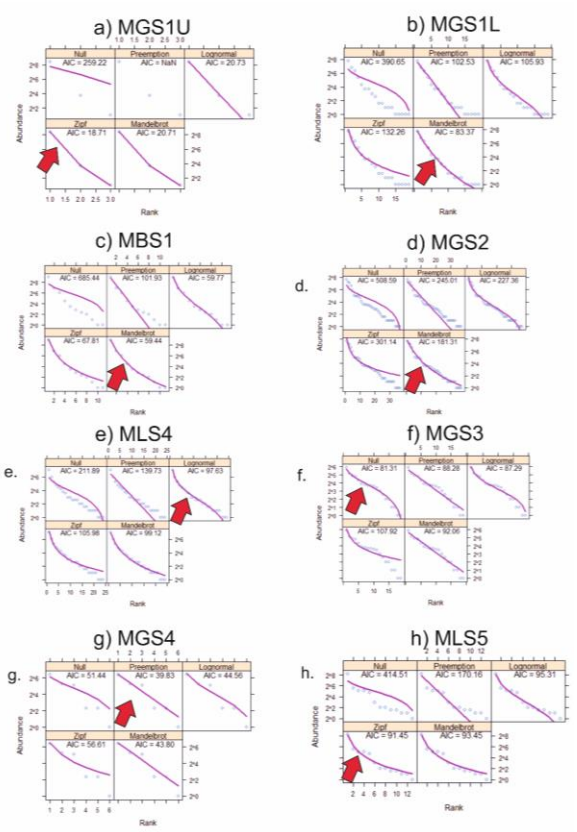


Figure 8. Rank-abundance models for the eight stratigraphic levels of Cambay Shale in Mangrol mine.

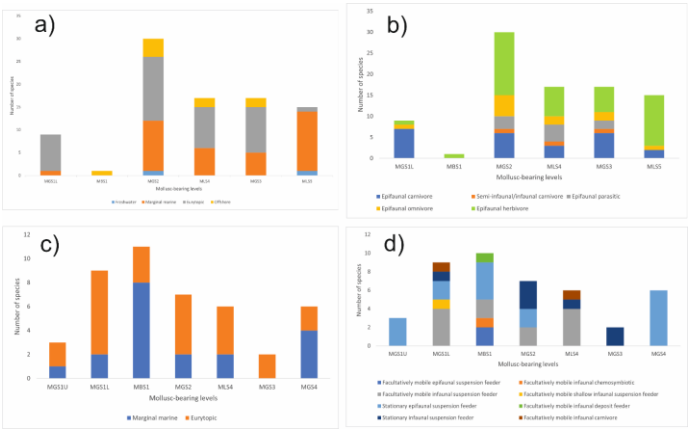


Figure 9. Bar diagrams showing the a) preferred environment and b) substrate and feeding habits of gastropods, and c) preferred environment and d) substrate, motility and feeding habits of bivalves, found in the Cambay Shale of Mangrol mine, based on literature review.

MB1 is composed of thick concretionary limestones with fragmented molluscs (MLS1 and MLS2) and a green shale (MGS1) with abundant intact molluscs. The lower part of MGS1 (MGS1L) is characterized by a shift towards larger gastropods (DCA, Fig. 6a), absence of microgastropods, scarce cerithioids, more eurytopic and less specialized gastropods (Lit. rev. Fig. 9a, c). A change in trophic structure from herbivore to carnivore-dominated (Lit. rev., Fig. 9b) also occurred at this level. Opportunist species, such as *Eopreangeria mangrolensis* sp. nov., dominated the assemblage (RAD: Zipf-Mandelbrot; Fig. 8b) with an overall lower diversity and higher dominance than MB2. However, dominance of a species is more pronounced in MB3 (DIs, Fig. 5). MGS1 exhibits the maximum proliferation of foraminifers, e.g., *Nummulites burdigalensis burdigalensis* de la Harpe, Schaub, 1981. Therefore, this part received more open-marine influence than other levels. The topmost level of this sequence is quite distinct (DCA, Fig. 6b; CA, Fig. 7) in having only stationary epifaunal suspension feeder bivalves, dominated by *Flemingostrea flemingi* (d'Archiac and Haime, 1854) with only a few other oysters (RAD: Zipf, Fig. 8a; DIs, Fig. 5; Lit. rev. Fig. 9d). This part represents the retreat of the sea, which culminated above into a swamp again that caused the development of Lignite 1. Marine fossils are absent from the upper part of the sequence overlying Lignite 1.

Therefore, this study deduced a gradual transition from a freshwater-dominated swamp (Lignite 2) to a relatively open-marine environment, later followed by a regressive phase, during the early Eocene in the Cambay Basin. The change in mollusc composition, diversity-abundance patterns, diversity indices and trophic structure, all contributed to the understanding of the dynamic interactions between species and their environment, and also the environmental evolution in the basin during early Eocene.

- **<u>A palaeoecological study of the Eocene of the Kutch Basin:</u>**

Located to the north of Cambay, contemporaneous sequences are found in the Kutch Basin. The Eocene of Kutch is represented by three formations – Naredi, Harudi and Fulra. While the Naredi and Harudi Formations are argillaceous, Fulra Limestone is a foraminiferal limestone. The plane laminated variegated shale succession of the former two are primarily deposits of quiet marginal marine waters. Green shale and limestone layers yielded fossils from these two formations. Lignite also occurs, mainly in the Naredi Formation. All these formations contain various marine fossil-bearing zones, rich in molluscs or foraminifers. Gastropods and bivalves dominate among the molluscs with only two reported nautiloids (Halder 2012). The molluscs are concentrated mainly in five stratigraphic levels within these three formations. These are – Level 1) Gypseous Shale Member, Naredi Formation, Level 2) *Assilina* Limestone Member, Naredi Formation, Level 3) Molluscan shell bed, Harudi Formation, Level 4) *Flemingostrea* bank, Harudi Formation, and Level 5) the basal part of Fulra Limestone.

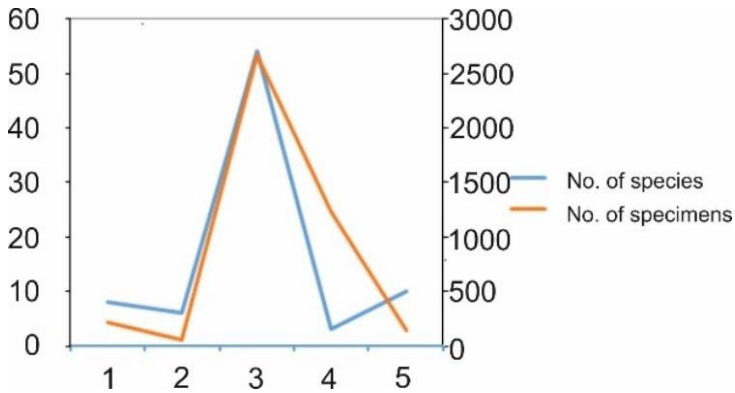


Figure 10. Species diversity and Total abundance of the five stratigraphic layers of Eocene of Kutch. Levels are discussed in text.

The molluscan shell bed of Harudi Formation has a distinctly larger diversity (number of species = 54; number of specimens = 2674) of molluscs than other levels, indicating a unique depositional condition (Fig. 10). A palaeosynecological study was conducted to understand this contrasting pattern and deduce the possible reasons behind this. A brief discussion of that study (Banerjee *et al*. 2019) is included here to make a comparison of the

palaeoenvironmental and palaeoecological conditions prevailing in the two adjacent basins of western India, Cambay and Kutch, during Eocene.

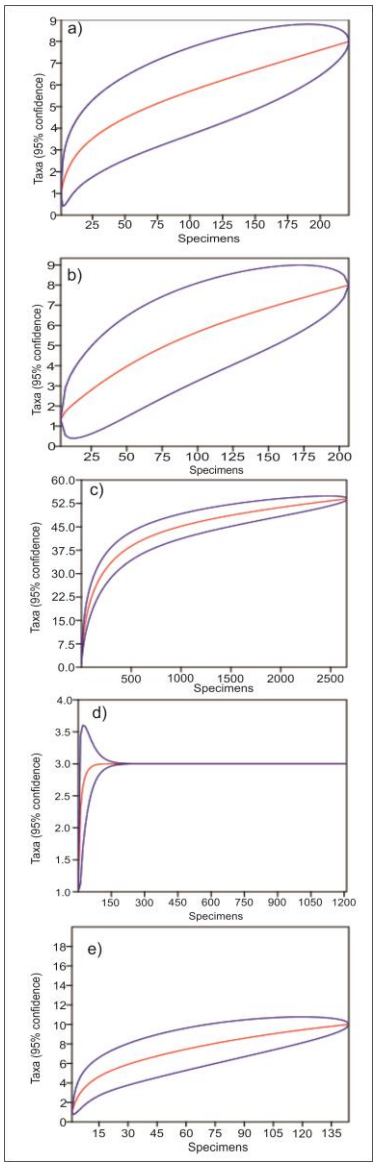


Figure 11. Rarefaction curves for the five stratigraphic levels within the Eocene of the Kutch Basin. a-e denote levels 1-5, as mentioned in the text.

Here, similar analyses including rarefaction analysis, rank-abundance diagram and literature review, were performed on the Kutch mollusc (gastropod and bivalve) data. Rarefaction curves validated sample size (Fig.11). Rank-abundance models helped to understand the changes in the palaeoenvironment in this sequence. A fit to the pre-emption model for Levels 1, 2 and 4 and Mandelbrot model for Level 5 indicated high abundance-low diversity assemblages, expected in a stressful and restricted environment (Fig. 12.a-b, d-e). On the contrary, Level 3 fits to the log-normal for, which implied a high diversity-low abundance assemblage, characteristic of a more stable and less stressful environment (Fig. 12c). Except for the molluscan shell bed, all other levels are dominated by a few mollusc species, with moderate to low abundances of other forms. The infaunal suspension feeder bivalves and epifaunal carnivore gastropods are dominant in the shell bed of Harudi Formation, a pattern common in present-day shallow open shelf. Therefore, based on the above observations, it was inferred that the molluscan shell bed was deposited in this restricted basin by storm surges, coming from the open part of the sea (Banerjee *et al*. 2019), whereas the other levels within the Naredi

and Harudi Formations were deposited in quiet and restricted parts of the basin under the influence of early Eocene transgression.

A similar lithological succession was developed in both the Cambay and Kutch basins under the influence of early Eocene transgression event. Similar diversity-abundance pattern also characterizes the contemporaneous fossil-bearing stratigarphic levels in these basins. The early Eocene of Cambay records a greater mollusc diversity than that of Kutch with greater marine influence. While the post-Ypresian was not found in the mine sections of Cambay, they could be studied in Kutch.

The molluscan diversity remained low and low-energy sediments such as variegated shales were deposited in this basin, in a marginal marine set-up, during the middle Eocene. Perturbations came in the form of a storm event that brought a diverse mollusc fauna in this restricted basin. The transport distance was short. The overlying upper Bartonian Fulra Limestone is the product of a carbonate platform. This was developed in response to a transgression due to Middle Eocene Climatic Optimum (MECO) (Saraswati *et al*. 2018), Mollusc diversity and also abundance are low here. A huge proliferation of larger benthic foraminifers (LBF) may have changed the substrate type that discouraged soft-bottom mollusc community. Huge proliferation of LBF in other stratigraphic levels such as, *Assilina* Limestone in the Naredi formation and *Nummulites obtusus* bed in the Harudi Formation are also characterized by only rare molluscs. These levels represent high influence of ocean in the basin, including maximum flooding zone (*Assilina* Limestone (Sarkar *et al*. 2012).

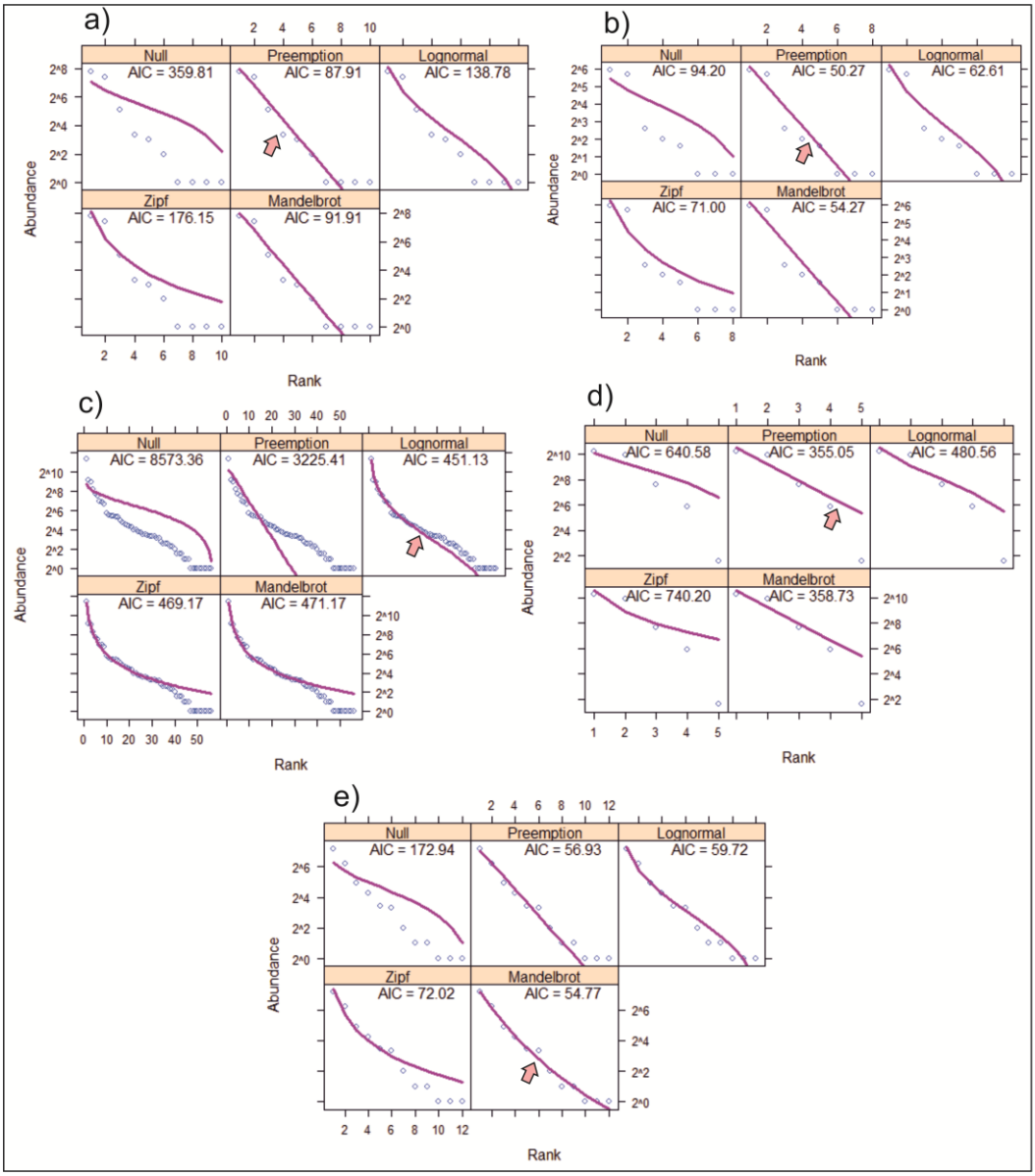


Figure 12. Rank-abundance models for the five stratigraphic levels within the Eocene succession of the Kutch Basin. a-e denote Levels 1-5 (mentioned in the text) respectively.

(3) BIOSTRATIGRAPHY:

3.1. MATERIALS & METHODS. Cluster analysis based on Bray-Curtis similarity index and using UPGMA algorithm, was carried out on the presence/absence data of the gastropods collected from the Cambay Shale from the three lignite mines - Mangrol, Vastan and Tadkeswar. It was also performed in PAST 3.20 software (Hammer *et al*. 2002). This

study is intended to understand how different mollusc-bearing layers in these sections are correlated with each other.

3.2. RESULTS & DISCUSSION. The dendrogram (Fig. 13) produced shows that the lowermost fossiliferous layer of Mangrol (MB3/MLS5) above Lignite 2 is correlatable to the fossiliferous layer present above Lignite 3 in the Vastan mine (see, Fig. 2). Both of these were deposited during the first marine incursion into this basin. The levels in MB2 of Mangrol with the greatest diversity of marine molluscs of the entire sequence, are clustered with the most mollusc-rich levels in the other two mines, with high similarity values. The dominance of brackish water specialized gastropods with several normal marine affiliated forms indicates the prevalence of an overall restricted environment. All these levels yield both macro and micro-gastropods. The upper-most gastropod-bearing level of the Mangrol mine (MGS1L) is clustered with the upper-most gastropod-bearing level (TGS1) of the Tadkeswar mine. These levels were deposited in a relatively more open marine condition compared with MB2 and MB3. In all three mines, limestones composed of micrite matrix and only fragmentary mollusc shells alternate with variegated shales. Mollusc fragments, wherever identifiable, are identical to those found intact in intervening shales. These limestones are products of perturbation and winnowing by relatively high energy regime within the otherwise calm and restricted coastal basin. Grey-black shales devoid of marine fossils are present in alternation with the fossiliferous green/brown shales or limestones, in all the sections. Therefore, the basin succession represents environmental changes and fluctuations in sea level in a transgressive sequence with frequent episodes of flooding, and intermittent regressive and aggradational phases during the early Eocene. The Cambay Shale from the Valia mine yielded only some turritellids. That is why it is not included in this analysis. The presence of several thick lignites, only a few marine fossil-bearing beds and

concentration of turritellids may indicate deposition in an estuary, within a transitional marine environment closer to land, in this part of the basin (Allmon 1988, 2011).

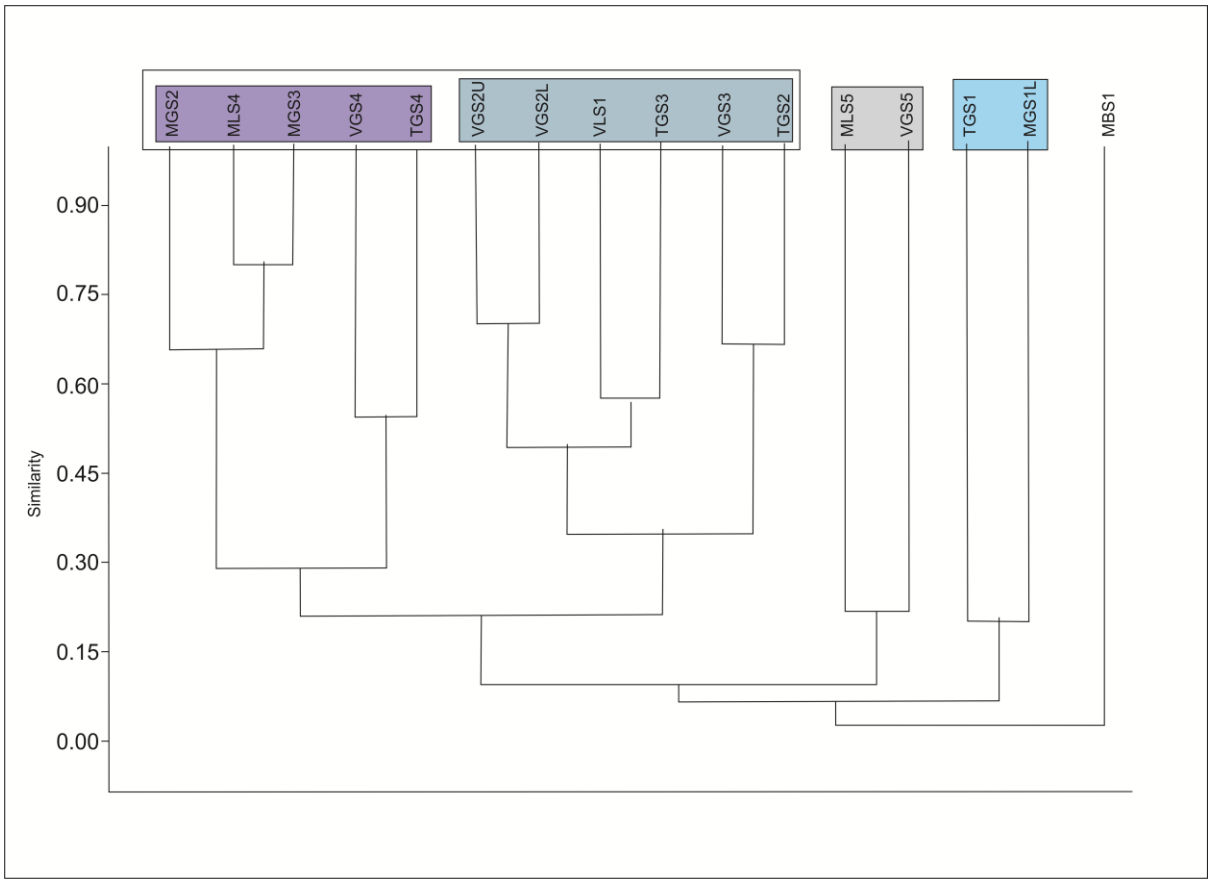


Figure 13. Dendrogram from Cluster Analysis showing correlation of different mollusc-bearing levels in the three mines.

(4) PALAEOBIOGEOGRAPHY:

With some exceptions revealed from the fossil record, the known and expected relations between geographic distribution, temporal range and early developmental modes are – 1) planktotrophs have greater geographic distributions than non-planktotrophs, 2) planktotrophs survive longer than non-planktotrophs, 3) non-planktotrophs speciate more rapidly than planktotrophs, and 4) geographic range of a genus and temporal range have influences over one another. After the taxonomic study of the Cambay gastropods revealed a remarkable

specific endemism and wide distribution of the genera, and the palaeoenvironmental study showed that the Cambay species lived and flourished under relatively restricted conditions in a marginal marine environment, an opportunity came to study the above-mentioned relations for this fauna. Such relations are better deciphered with bigger data. That is why the Paleocene-Eocene gastropod fauna of WIP is taken into account here. For an overall understanding of the palaeobiogeographic evolution of this fauna, the roles of ocean surface currents and climate changes were also studied.

4.1. MATERIALS & METHODS.

a) Spatial and temporal ranges of all the species and the genera they belong to, recorded from the Paleocene-Eocene of WIP, were gathered from literature and an online database, Paleobiology Database (PBDB).

b) Protoconch types of the Cambay Basin species were deduced based on the Apex theory (Thorson 1950) and D/Vol ratio (Shuto 1974). Protoconch types of the species and genera of other basins of WIP were deduced from published literature.

c) The number of occupied equal-area hexagonal grid cells (Darroch *et al*. 2020; Jones *et al.* 2023) were calculated for the WIP genera (total genera: 146; cell calculated in 132 having continuous fossil record) in different ages, starting from Cretaceous to Pleistocene. These calculations were performed using the 'palaeoverse' package of R.

d) The temporal range (T_{tot}), time (T_1) taken by the genera to reach its peak geographic distribution, R_{max} and the remaining time (T_2) the genera persisted after reaching R_{max} were calculated. Then reduced major axis regression (RMA) method was used to understand whether the pairs, R_{max}/T_1 and R_{max}/T_2. have linear/nonlinear relations in between. Mann-Whitney U-tests were performed to check whether the R_{max} and T_{tot} were significantly

different between the genera having only non-planktotrophic development and those having either only planktotrophic/both kinds of development. These calculations were performed in PAST 3.20 software (Hammer *et al*. 2001).

d) The highest latitudinal occurrence of the WIP genera during the epochs of the Palaeogene period were compiled separately for the northern and southern hemispheres from PBDB. The percentage of genera that showed an increase, decrease and no change in the highest latitudinal occurrence across the age boundaries were calculated and represented in bar diagrams.

4.2. RESULTS & DISCUSSION.

a) *How did ocean surface currents control the dispersal of WIP genera during the Paleocene-Eocene?*

The WIP genera showed a cosmopolitan distribution during the Paleocene-Eocene, mainly occurring in the eastern and western sides of the relict Tethys Sea, the western and eastern coasts of the Atlantic Ocean, and the western and eastern coasts of the North Pacific Ocean. However, they were scarce in the southern hemisphere basins of Australia, New Zealand and Antarctica. This supports the previous studies which showed the east-west flowing equatorial current drove the dispersal of marine benthic fauna but restricted similar exchanges between the northern and southern hemisphere basins (Haq 1981; Das & Halder 2019). Contradictory opinions are found in the understanding of the directions of these currents, especially the Tethys current. Haq (1981, 1988) postulated a westward Tethys current in Paleocene-Eocene whereas Barron & Peterson (1991) modelled a weak eastward current. This study revealed that 1) 14 out of the 20 species that the WIP shares with other provinces, appeared earlier on the eastern side of the Tethys than on the western side of it, 2) out of the 142 genera recorded

in the Paleocene-Eocene of WIP maximum (40/28.2%) have their first occurrences in Ypresian. 25 among them appeared first in WIP and later in other provinces, 11 of them appeared in the same age in WIP and other provinces, and 4 of them appeared first in other provinces and later in WIP. Therefore, this study supports Haq's (1981, 1988) view of a westward movement of the Tethys current.

b) *Is the endemism/provincialism of species in the Cambay and other basins of WIP due to the lack of planktotrophy in them?*

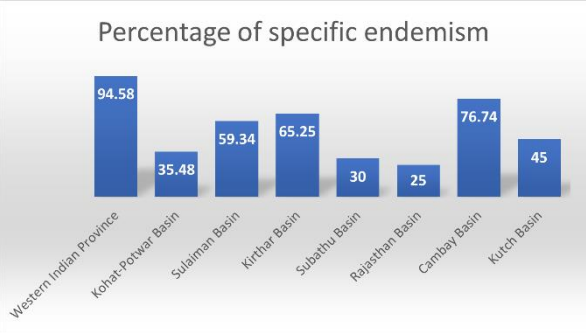


Figure 14. Percentage of specific endemism within the basins of WIP.

Gastropods have a diverse development strategy. In general, those lacking the planktotrophic larval stage are considered to have restricted distribution, i.e., endemic. A significant amount of endemism is noticed within the gastropod fauna of all basins of WIP, including Cambay (Fig. 14).

The mode of development was deduced for 24 species of the Cambay fauna, following the 'Apex Theory' and 'D/Vol ratio' methods. Only 3 species had direct development, 3 had lecithotrophic development, and 18 had planktotrophic development. When the entire WIP is considered, the shares of planktotroph (~52%) and non-planktotroph species (~48%) are close. However, protoconch could be observed only in 27% of the entire WIP gastropod fauna.

The above numbers point towards the dominance of planktotrophy within the Paleocene-Eocene gastropod species of the Cambay Basin and the other basins of WIP. Therefore, the endemism/provincialism of these faunas did not occur due to the lack of planktonic larvae in

them. It contradicts the common notion. WIP genera speciated rapidly in allopatry after long-distance migration even involving trance-oceanic routes. That several basins of WIP had quite distinct faunas perhaps reflects the isolated and restricted nature of the basins. Here, the non-allopatric modes, such as peripatric speciation driven by ecological divergence, or allopatry occurring at much smaller geographic scale, might be responsible for diversification. Future studies need to address this feature to see if this pattern is global.

c) *To what extent does the mode of development, i.e., presence/absence of planktotrophy, control the cosmopolitan distribution of the genera that appeared in WIP during the Paleocene and Eocene*? *Did these genera attain their wide geographic spread quickly? Was this controlled by the mode of development? Did the mode of development also control the overall temporal range of the genera?*

Out of the 132 WIP genera for which the geographic grid cell calculation could be performed, a majority (72/54.54%) attained their maximum geographic distribution during the Paleocene-Eocene. 3 of them achieved it in Paleocene, 15 in early Eocene, 50 in middle Eocene and 4 in late Eocene.

A positive correlation is revealed between the R_{max} and T_1 ($p < 0.05$, $r = 0.496$). Therefore, more time the WIP genera took to reach their peak geographic distribution, the distribution continued to broaden, a pattern commonly recorded (Foote *et al*. 2008 and references therein). However, no positive correlation is found between R_{max} and T_2 ($p = 0.02$, $r = -0.22$), which is unlikely because greater geographic range commonly found to ensure greater durability (Jablonski 1987, 1996; Foote *et al*. 2008 and references therein). These relations were further studied from the fossil records of the WIP genera and the families they belong to.

Most fossil species of gastropods belonging to the Cypraeoidea and Olivoidea, including those reported from the WIP, are known by non-planktotrophic development, especially direct development. Despite that, they had wide geographic distributions (Meyer 2003; Kilburn 1981; Landau & Silva 2006). Therefore, the commonly held view about non-planktotrophy limiting spatial range does not hold for these gastropods. On the other hand, while the WIP Cypraeoidea spread to their maximum geographic extent quite rapidly and were extinct by late Eocene, the Olivoidea took longer time to reach its geographic acme and also lasted longer (Fig. 15b, c). Palaeogene Volutoidea, including those reported from the WIP, are mostly known by non-planktotrophic development although planktotrophy was not rare

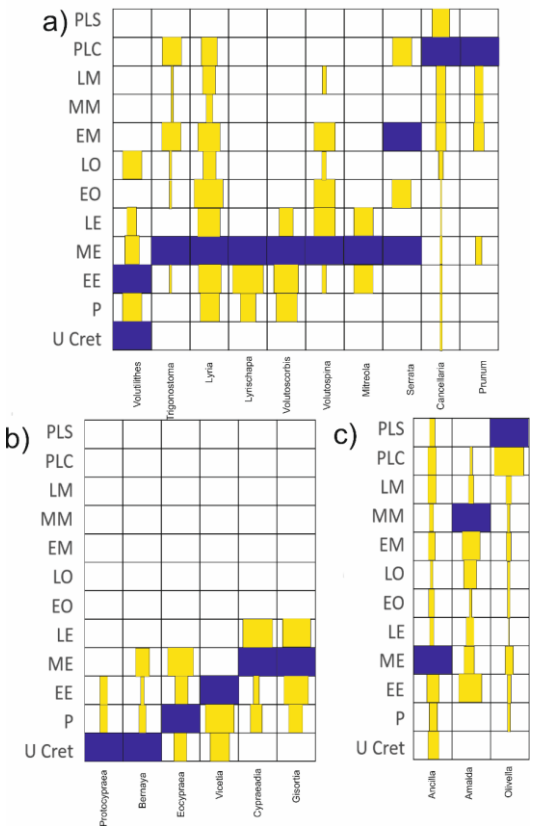


Figure 15. Number of cells occupied by a) Volutoidea, b) Cypraeoidea, and c) Olivoidea of WIP, from the Upper Cretaceous to Pleistocene. Non-planktotrophic development is dominant in all of them.

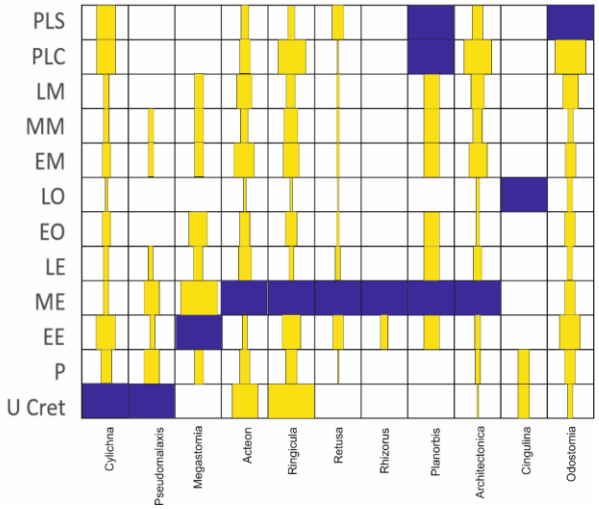


Figure 16. Number of cells occupied by heterobranch gastropods of WIP, from the Upper Cretaceous to Pleistocene.

in them. Early rapid distributions (Fig. 15a), and inconsistent relations between the mode of development and spatial-temporal ranges are also observed in the volutids.

In Cerithioidea, a direct relation between planktotrophy and wide geographic distribution is often observed. Here also, the attainment of the maximum geographic distribution shortly after their origin is noticed (Fig. 17c). This pattern is also observed within the representatives of the superfamilies Campaniloidea, Naticoidea, Stromboidea, Conoidea, and Buccinoidea within the caenogastropods, and also within some genera belonging to the subclass Heterobranchia, where most genera are found to have maximum geographic distribution during the middle Eocene. (Figs. 16,17). All of these are known by either only planktotrophic/both types of development. *Muricopsis* and *Phyllonotus*, the muricoids of WIP stand in contrast to this. They show non-planktotrophic development, restricted spatial duration and slow geographic spread over time (Fig. 17a).

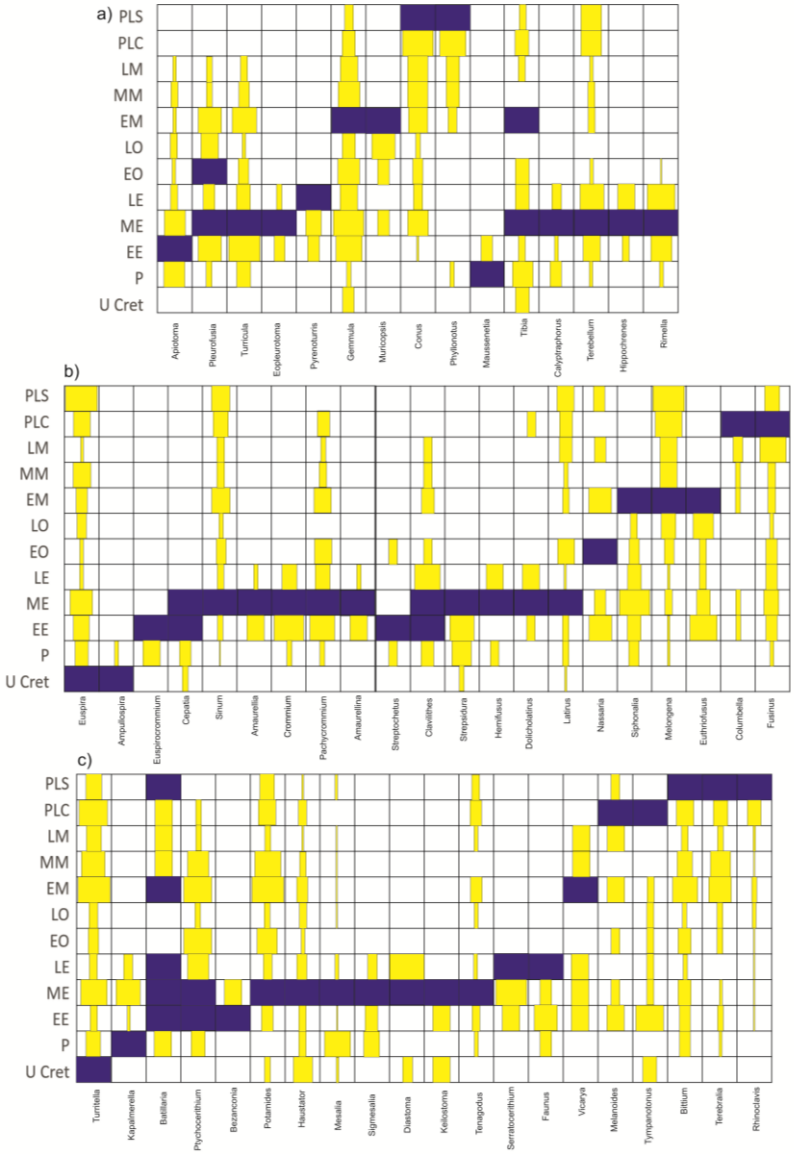


Figure 17. Number of cells occupied by a) Conoidea, Muricoidea, Stromboidea, b) Campaniloidea, Naticoidea, Buccinoidea and c) Cerithioidea group of gastropods of WIP, from the Upper Cretaceous to Pleistocene.

In addition to this, a considerable

number (24/18.18% of the total) of genera are found to occupy the maximum number of cells during Pleistocene (Fig. 18). Their peak geographic distribution is not attained at their early history, unlike most other genera of this assemblage.

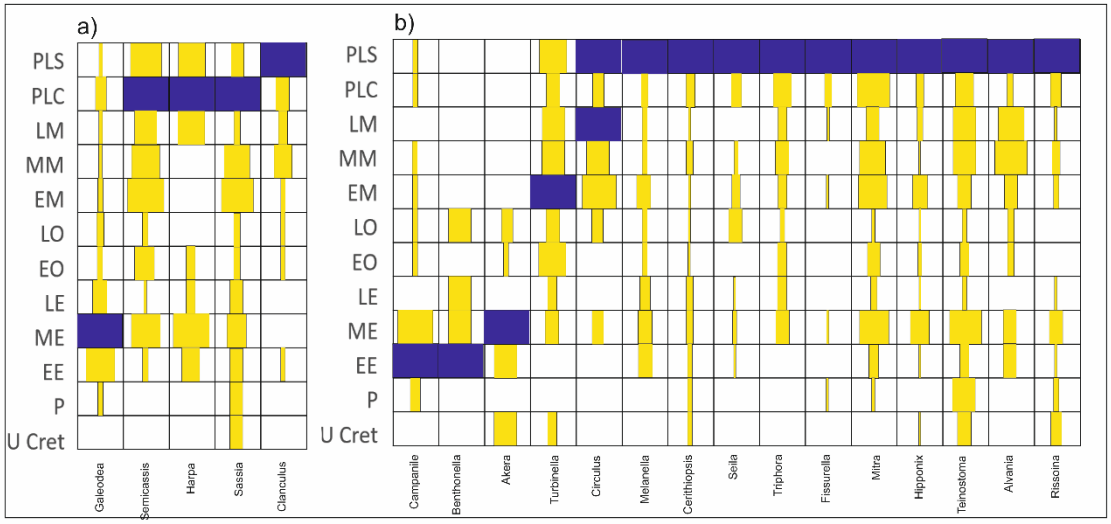


Figure 18. Number of cells occupied by a) Tonnoidea and b) all other remaining gastropods of WIP, from the Upper Cretaceous to Pleistocene. A greater temporal span was required for most of these genera to attain the maximum geographic distribution.

The results of the Mann-Whitney U-tests showed that the maximum geographic range and the entire temporal range are not significantly different for the non-plankotrophs and the genera having either only planktotrophic/both types of development.

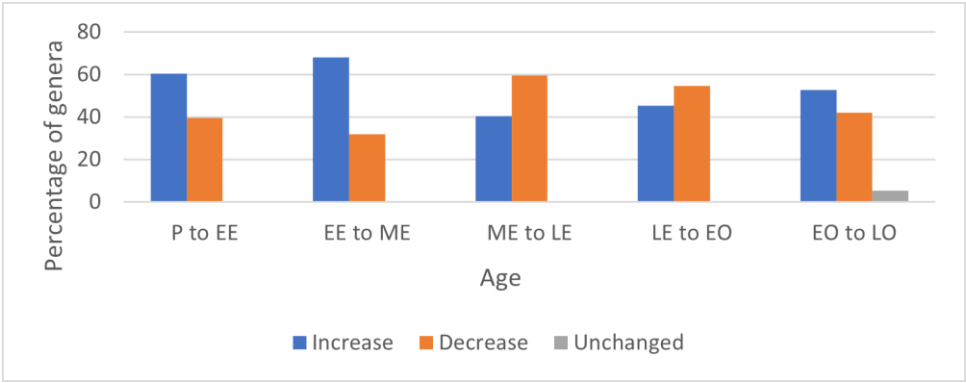
This study has shown that in majority of the Paleocene-Eocene gastropod genera recorded from the WIP, the presence of planktotrophy can be linked with wide geographic and temporal distribution, and an early attainment of maximum geographic distribution. However, the absence of planktotrophy did not necessarily lead to opposite consequences. Non-planktotroph genera with rapidly developed wide distribution and long temporal range were found. Migration mechanisms of gastropods lacking planktonic larval phases need to be explored. Dispersal of adult gastropods via rafting on macroalgae (Highsmith 1985; Donald

et al. 2005), and migration of a direct developer genus, *Galeodea*, by mucous strings secreted by their juveniles (Beu 2008) were documented in some studies. It is also found here that most genera attained their maximum geographic range in their early history (~55% showed peak geographic distribution within Paleocene-Eocene). Moreover, more time these genera took to reach that peak, the peak became wider.

e) *How did WIP gastropod genera respond to climate changes of the Palaeogene period?*

The WIP gastropods had to survive several climatic fluctuations through Paleogene. The Paleocene-Eocene (PE) boundary is globally demarcated by a sharp increase in temperature (Sluijs *et al*. 2008) whereas the Eocene-Oligocene (EO) boundary marks the onset of Cenozoic icehouse condition and formation of polar cryosphere (Ogasawara *et al*. 2008). There are other warming and cooling events during Paleogene, such as, several short-lived early Eocene hyperthermals, Middle Eocene Climatic Optimum (MECO) and terminal Eocene cooling already during late Eocene that culminated into EO icehouse. In the northern hemisphere, more genera showing an increase in their maximum latitude in the PE and early Eocene/middle Eocene boundaries might be due to the effects of the two well-documented warming events at these boundaries, i.e., PETM and MECO respectively (Fig. 19a). On the other hand, cooling events that tend to push benthic animals towards lower latitudes, are reflected in the decrease in maximum latitude of a greater number of genera at middle/late Eocene and EO boundaries. More genera showing an increase in maximum latitude position in the northern hemisphere, at the early/late Oligocene boundary also fits with the late Oligocene warming event (O'Brien *et al*. 2020). These patterns are not clear in southern hemisphere because of sparse data (Fig. 19b).

a)



b)

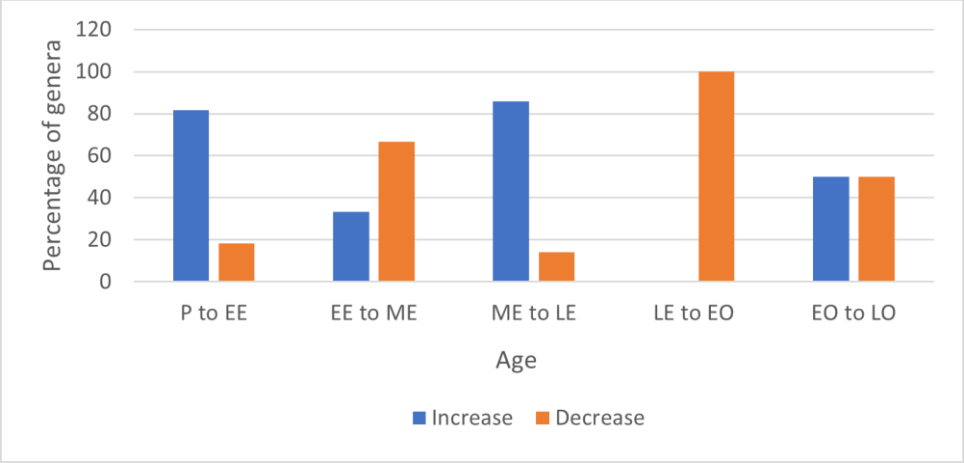


Figure 19. Column diagrams showing changes in maximum latitudinal occurrences of WIP genera in five age boundaries within Palaeogene for (a) northern and (b) southern hemispheres.

References.

1. ALLMON, W. D. 1988. Ecology of Recent turritelline gastropods (Prosobranchia, Turritellidae): current knowledge and paleontological implications. *Palaios*, **3**, 259-284.
2. ALLMON, W. D. 2011. Natural history of turritelline gastropods (Cerithiodea: Turritellidae): a status report. *Malacologia*, **54** (1-2), 159-202.
3. BANERJEE, S., DAS, S., HALDER, K. and CHAKRABARTI, N. 2019. Palaeoecological Analysis of Benthic Molluscs from the Eocene of Kutch, Gujarat

Reveals an Event of Storm Induced Concentration of Shells in a Quiet Marginal Marine Environment. *Journal of the Geological Society of India*, **94** (2), 162–170.

4. BARRON, E. J. and PETERSON, W. H. 1991. The Cenozoic ocean circulation based on ocean General Circulation Model results. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **83** (1-3), 1-28.
5. BEU A. G. 2008. Recent deep-water Cassidae of the world. A revision of *Galaeodea*, *Oocorys*, *Sconsia*, *Echinophoria* and related taxa, with new genera and species (Mollusca, Gastropoda), *in* HEROS V., COWIE R. H. & BOUCHET P. (eds), Tropical Deep-Sea Benthos 25. *Mémoires du Muséum national d'Histoire naturelle* 196, 269-387. Paris.
6. CHANDRA, P. K. and CHOWDHARY, L. R. 1969. Stratigraphy of the Cambay Basin. *Bulletin Oil and Natural Gas Commission.* **6**, 37–50.
7. CLEMENTZ, M., BAJPAI, S., RAVIKANT, V., THEWISSEN, J. G. M., SARAVANAN, N., SINGH, I. B. and PRASAD, V. 2011. Early Eocene warming events and the timing of terrestrial faunal exchange between India and Asia. *Geology*, **39** (1), 15–18.
8. COSSMANN, M. and PISSARRO, G. 1909. The Mollusca of the Ranikot Series, Part 1, Cephalopoda and Gastropoda. *Memoirs of the Geological Survey of India, Palaeontologia Indica, New Series,* **3** (1), 1–83.
9. COX, L. R. 1930. The fossil fauna of the Samana Range and some neighbouring areas: The Mollusca of the Hangu Shales. Memoirs of the Geological Survey of India, *Palaeontologia Indica, New Series*, **15**, 129–222.
10. COX, L. R. 1931. A contribution to the molluscan fauna of the Laki and basal Kirthar groups of the Indian Eocene. *Transactions of the Royal Society of Edinburg.* **57**, part 1, (2), 25–92.

11. D'ARCHIAC, L. V. and HAIME, J. 1854, Description des Animaux Fossiles du Groupe Nummulitique de l'Inde, Seconde Livraison, Mollusques. *Paris, Gide et J. Baudry.* 225–373.
12. DARROCH, S.A., CASEY, M.M., ANTELL, G.S., SWEENEY, A. and SAUPE, E.E. 2020. High preservation potential of paleogeographic range size distributions in deep time. *The American Naturalist*, **196** (4), 454-471.
13. DAS, S. 2019. Systematics, palaeobiogeography and palaeoecology of the Eocene gastropoda (mollusca) from Kutch, Gujarat. Unpublished PhD thesis, Presidency University.
14. DAS, S. and HALDER, K. 2018. Control of climate and Tethyan legacy on distribution of Paleocene–Eocene gastropods and establishment of the Northern Tropical Realm. *Journal of Earth System Science*, **127** (4), 1–5.
15. DAS, S. and HALDER, K. 2018. Control of climate and Tethyan legacy on distribution of Paleocene–Eocene gastropods and establishment of the Northern Tropical Realm. *Journal of Earth System Science*, **127** (4), 1–5.
16. DESHAYES, G. P. 1862. Description des animaux sans vertèbres découverts dans le bassin de Paris pour servir de supplément à la Description des coquilles fossiles des environs de Paris comprenant une revue générale de toutes les espèces actuellement connues. *Tome deuxiéme. Mollusques acéphalés monomyaires et Brachiopodes. Mollusques céphalés, Première partie*. Paris, Baillière, 27–39.
17. DONALD K. M., KENNEDY M., SPENCER H. G. 2005. Cladogenesis as the result of long-distance rafting events in South Pacific topshells (Gastropoda, Trochidae). *Evolution*, **59**, 1701–11.
18. EAMES, F. E. 1952. A contribution to the study of the Eocene in western Pakistan and western India, C, The description of the Scaphopoda and Gastropoda from standard

sections in the Rakhi Nala and Zinda Pir areas of the western Punjab and in the Kohat District. *Philosophical Transactions of the Royal Society of London, B, Biological Sciences*, **236** (631), 1–168.

19. FOOTE, M., CRAMPTON, J.S., BEU, A.G. and COOPER, R.A., 2008. On the bidirectional relationship between geographic range and taxonomic duration. *Paleobiology*, **34** (4), 421-433.
20. GARG, R., ATEEQUZZAMAN, K., PRASAD, V., TRIPATHI, S. K. M., SINGH, I. B., JAUHRI, A. K. and BAJPAI, S. 2008. Age–diagnostic dinoflagellate cysts from the lignite–bearing sediments of the Vastan lignite mine, Surat District, Gujarat, western India. *Journal of the Palaeontological Society of India*, **53** (1), 99–105.
21. HALDER, K. 2012. Cenozoic fossil nautiloids (Cephalopoda) from Kutch, western India. *Palaeoworld*, **21**, 116–130.
22. HALDER, K. and BANO, S. 2015. Cenozoic Corbulidae (Bivalvia, Mollusca) from the Indian subcontinent–Palaeobiogeography and revision of three species from Kutch, India. *Arabian Journal of Geosciences*, **8**, 2019–2034.
23. HALDER, K. and DAS, S. 2019. New subfamily Indovolutinae and other volutids (Volutidae, Gastropoda) from the Eocene of Kutch, western India and their paleobiogeographic implications. *Journal of Paleontology*, **93** (5), 899–915.
24. HALDER, K. and SINHA, P. 2014. Some Eocene cerithioids (Gastropoda, Mollusca) from Kutch, western India, and their bearing on palaeobiogeography of the Indian subcontinent. *Paleontology Journal*, **2014**, art. id. 673469.
25. HAMMER, Ø., HARPER, D. A. T. and RYAN, P. D. 2001. PAST, Paleontological statistics software package for education and data analysis. *Palaeontologia Electronica*, **4** (1), 9.

26. HAQ, B. U. 1981. Paleogene paleoceanography: Early Cenozoic oceans revisited. *Oceanologica Acta, Special issue*, 71–82.
27. HAQ, B.U. 1988. Geological evolution of the Indian Ocean with special reference to the Arabian Sea. In *Marine science of the Arabian Sea. Proceedings of an International Conference (March 1986). American Institute of Biological Sciences, Washington, DC* (pp. 9-35).
28. HARZHAUSER, M., REUTER, M., PILLER, W. E., BERNING, B., KROH, A. and MANDIC, O. 2009. Oligocene and Early Miocene gastropods from Kutch (NW India) document an early biogeographic switch from Western Tethys to Indo–Pacific. *Paläontologische Zeitschrift*, **83** (3), 333–372.
29. HIGHSMITH, R. C. 1985. Floating and algal rafting as potential dispersal mechanisms in brooding invertebrates. *Marine ecology progress series Oldendorf*, **25** (2), 169-179.
30. IQBAL, M. W. A. 1969a. Mega–fauna from the Ghazij Formation (lower Eocene) Quetta Shahrig area, West Pakistan. *Memoirs of the Geological Survey of Pakistan, Palaeontologia Pakistanica,* **5**, 1–41.
31. IQBAL, M. W. A. 1969b. The Tertiary pelecypod and gastropod fauna from Drug, Zindapir, Vidor (district D. G. Khan), Jhalar and Chharat (district Campbellpore), West Pakistan. *Memoirs of the Geological Survey of Pakistan, Palaeontologia Pakistanica*, **6**, 1–95.
32. IQBAL, M. W. A. 1972. Palaeocene bivalve and gastropod fauna from Jherruk Lakhra–Bara Nai (Sind), Salt Range (Punjab) and Samana Range (N. W. F. P.), Pakistan. *Memoirs of the Geological Survey of Pakistan, Palaeontologia Pakistanica*, **9**, 1–105.
33. JABLONSKI, D. 1987. Heritability at the species level: analysis of geographic ranges of Cretaceous mollusks. *Science*, **238** (4825), 360-363.

34. JONES, L. A., GEARTY, W., ALLEN, B. J., EICHENSEER, K., DEAN, C. D., GALVÁN, S., KOUVARI, M., GODOY, P. L., NICHOLL, C. S., BUFFAN, L. and DILLON, E. M. 2023. Palaeoverse: A community-driven R package to support palaeobiological analysis. *Methods in Ecology and Evolution*.
35. KHOZYEM, H., ADATTE, T., KELLER, G. and SPANGENBERG, J. E. 2021. Organic carbon isotope records of the Paleocene–Eocene Thermal Maximum event in India provide new insights into mammal origination and migration. *Journal of Asian Earth Sciences*, **212**, 104736.
36. KILBURN, R. N. 1981. Revision of the genus *Ancilla* Lamarck, 1799 (Mollusca: Olividae: Ancillinae). *Annals of the Natal Museum*, **24** (2), 349–463.
37. KULKARNI, K. G., KAPOOR, S. B. and BORKAR, V. D. 2010. Molluscan fauna from the Miocene sediments of Kachchh, Gujarat, India – Part 3. Gastropods. *Journal of Earth System Science*, **119** (3), 307–341.
38. LANDAU, B. and SILVA, C. M. D. The Early Pliocene Gastropoda (Mollusca) of Estepona, Southern Spain. *Palaeoeontos*, **9**, 1–21.
39. LEYMERIE, A. 1846. Mémoire sur le terrain à Nummulites (Epicrétacé) des Corbières et de la Montagne Noire. *Mémoires de la Société Géologique de France 2*, **1**, 337–373 pp.
40. MEYER, C.P. 2003. Molecular systematics of cowries (Gastropoda: Cypraeidae) and diversification patterns in the tropics. *Biological Journal of the Linnean Society*, **79** (3), 401-459.
41. NAGORI, M. L., KHOSLA, S. C. and JAKHAR, S.R., 2013. Middle Eocene Ostracoda from the Tadkeshwar Lignite Mine, Cambay Basin, Gujarat. *Journal of the Geological Society of India*, **81** (4), 514–520.

42. O'BRIEN, C. L., HUBER, M., THOMAS, E., PAGANI, M., SUPER, J.R., ELDER, L.E. and HULL, P. M. 2020. The enigma of Oligocene climate and global surface temperature evolution. *Proceedings of the National Academy of Sciences*, **117** (41), 25302-25309.
43. OGASAWARA, K., TAKANO, M., NAGATO, H. and NAKANO, T. 2009. Cenozoic molluscan faunas and climatic changes in the northern Pacific related to Pacific gateways, review and perspective. *Bulletin of the Geological Survey of Japan*, **59** (7-8), 355-364.
44. OKSANEN, J. 2013. Vegan: ecological diversity. *R project*, **368**, 1-11.
45. PRASAD, V., SINGH, I.B., BAJPAI, S., GARG, R., THAKUR, B., SINGH, A., SARAVANAN, N. and KAPUR, V. V., 2013. Palynofacies and sedimentology–based high–resolution sequence stratigraphy of the lignite–bearing muddy coastal deposits (early Eocene) in the Vastan Lignite Mine, Gulf of Cambay, India. *Facies*, **59** (4), 737–761.
46. PUNEKAR, J. AND SARASWATI, P.K. 2010. Age of the Vastan lignite in context of some oldest Cenozoic fossil mammals from India. *Journal Geological Society of India*, **76**, 63–68.
47. SAHNI, A., SARASWATI, P. K., RANA, R. S., KUMAR, K., SINGH, H., ALIMOHAMMADIAN, H., SAHNI, N., ROSE, K. D., SINGH, L. and SMITH, T. 2006. Temporal constraints and depositional palaeoenvironments of the Vastan lignite sequence, Gujarat: Analogy for the Cambay Shale hydrocarbon source rock. *Indian Journal of Petroleum Geology*, **15** (1), 1–20.
48. SAMANTA, A., BERA, M. K. and SARKAR, A. 2016. Climate-modulated sequence development in a tropical rift basin during the Late Palaeocene to Early Eocene super greenhouse Earth. *Sedimentology*, **63** (4), 917–939.
49. SAMANTA, A., BERA, M. K., GHOSH, R., BERA, S., FILLEY, T., PANDE, K., RATHORE, S. S., RAI, J. and SARKAR, A. 2013. Do the large carbon isotopic

excursions in terrestrial organic matter across Paleocene–Eocene boundary in India indicate intensification of tropical precipitation? *Palaeogeography, Palaeoclimatology, Palaeoecology*, **387**, 91–103.

50. SARASWATI, P. K., KHANOLKAR, S. and BANERJEE, S. 2018. Paleogene stratigraphy of Kutch, India: an update about progress in foraminiferal biostratigraphy. *Geodinamica Acta*, 30 (1), 100-118.
51. SARKAR, U., BANERJEE, S. and SARASWATI, P. K. 2012. Integrated borehole and outcrop study for documentation of sea level cycles within the Early Eocene Naredi Formation, western Kutch, India. *Journal of Palaeogeography*, **1** (2), 126-137.
52. SCHAUB, H. 1981. Nummulites et Assilines de la Tethys Paleogene Taxinomie, Phylogenese et Biostratigraphie. *Mem. Suisses Paleont*, **104-106**, 236.
53. SHUTO, T. 1974. Larval ecology of prosobranch gastropods and its bearing on biogeography and paleontology. *Lethaia*, **7** (3), 239–256.
54. SLUIJS, A., BRINKHUIS, H., CROUCH, E. M., JOHN, C. M., HANDLEY, L., MUNSTERMAN, D., BOHATY, S. M., ZACHOS, J. C., REICHART, G. J., SCHOUTEN, S. and PANCOST, R. D. 2008. Eustatic variations during the Paleocene–Eocene greenhouse world. *Paleoceanography*, **23** (4), 4216.
55. SUDHAKAR, R. and BASU, D. N. 1973. A reappraisal of the Paleogene stratigraphy of southern Cambay Basin. *Bulletin Oil and Natural Gas Commission*, **10**, 55–76.
56. THORSON, G. 1950. Reproductive and larval ecology of marine bottom invertebrates. *Biological reviews*, **25** (1), 1–45.
57. VREDENBURG, E. W. 1923a. Indian Tertiary Gastropoda, IV. Olividae, Harpidae, Marginellidae, Volutidae and Mitridae, with comparative diagnosis of new species. *Records of the Geological Survey of India*, **54**, 243–276.
58. https://science.mnhn.fr/institution/mnhn/search.

Research article published from this work -

1. Banerjee, S., Das, S., Halder, K. and Chakrabarti, N. 2019. Palaeoecological Analysis of Benthic Molluscs from the Eocene of Kutch, Gujarat Reveals an Event of Storm Induced Concentration of Shells in a Quiet Marginal Marine Environment. *Journal of the Geological Society of India*, **94** (2), 162-170.

Abstracts published from this work –

1. Banerjee, S., Das, S. and Halder, K. 2018. Palaeoecological analysis of gastropods from the Eocene of Kutch, Gujarat reveals storm induced concentration in shell bed within a quiet marginal marine setting. In *National Seminar on Effects of Paleo and Anthropogenic Events on Earth System & Annual General Meeting of Geological Society of India,* p. 32-33.

2. Banerjee, S., Halder, K. and Aich, S., 2019. Analysis of molluscan shell beds from lower Eocene deposits of Cambay Basin, Western India reveals proliferation of opportunist taxa in the coastal sheltered environment in response to transgressions. In *Geological Society of America Annual Meeting*, no. 196-13.

3. Banerjee, S. and Halder, K. 2020. Lower Eocene Cambay Shale from Vastan mines, Gujarat: product of a sheltered coastal environment as revealed from mixed facies gastropod assemblage and proliferation of opportunist taxa. In *International Geological Congress*, p. 676-677.

4. Banerjee, S. and Halder, K. 2021. Composition and diversity-abundance pattern of molluscs reveal heterogeneity in micro-habitats in a linear coastal setting from the lower Eocene of western India. In *3rd Palaeontological Virtual Congress*, p. 238.